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Wake-Vortex Hazards During Cruise

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EXTENDED ABSTRACT
Summary

Even though the hazard posed by lift-generated wakes of subsonic transport aircraft has been studied extensively for approach and departure at airports, only a small amount of effort has gone into the potential hazard at cruise altitude. This paper reports on a study of the wake-vortex hazard during cruise because encounters may become more prevalent when free-flight becomes available and each aircraft is free to choose its own route between destinations. In order to address the problem, the various fluid-dynamic stages that vortex wakes usually go through as they age will be described along with estimates of the potential hazard that each stage poses. It appears that a rolling-moment hazard can be just as severe at cruise as for approach at airports, but it only persists for several minutes. However, the hazard posed by the downwash in the wake due to the lift on the generator aircraft persists for tens of minutes in a long narrow region behind the generating aircraft. The hazard consists of severe vertical loads when an encountering aircraft crosses the wake. A technique for avoiding vortex wakes at cruise altitude will be described.

To date the hazard posed by lift-generated vortex wakes and their persistence at cruise altitudes has been identified and subdivided into several tasks. Analyses of the loads to be encountered are underway and should be completed shortly. A review of published literature on the subject has been nearly completed (see text) and photographs of vortex wakes at cruise altitudes have been taken and the various stages of decay have been identified. It remains to study and sort the photographs for those that best illustrate the various stages of decay after they are shed by subsonic transport aircraft at cruise altitudes. The present status of the analysis and the paper are described in the following extended abstract.

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Nomenclature

AR	=aspect ratio
b	=wing span, $ft.$
b'	=spanwise distance between vortex centers, $ft.$
B	=breadth, $ft.$
c	=wing chord, $ft.$
C_L	=lift coefficient = L/qS
C_l	=rolling-moment coefficient=M/qSb
D	=depth, $ft.$
L	=lift, $lbs.$
M	=rolling moment, $ft. - lbs.$
q	=dynamic pressure = $\rho U_\infty{}^2/2$, $lbs./ft.^2$
S	=wing planform area, $ft.^2$
t	=time, $sec.$
U_∞	=velocity of aircraft, $ft./sec.$
Wt	=weight of aircraft, $lbs.$
x	=distance in flight direction, $ft.$
y	=distance in spanwise direction, $ft.$
z	=distance in vertical direction, $ft.$
Γ	=vortex strength,$ft.^2/sec.$
ρ	=air density, $slugs/ft.^3$

Subscripts

ac	=aircraft
app	=approach
dep	=departure
f	=following aircraft
fcr	=flight corridor
g	=wake-generating aircraft
hz	=hazardous region of wake
int	=intersection

m =maximum

o =centerline

td =travel distance

v =vortex

wk =wake

$wind$ =wind

Introduction

The dynamics, persistence and hazard posed by the vortex wakes of aircraft in the vicinity of an airport, and especially during landing and takeoff, has been under study for some time[1-6]. Fig. 1 depicts the types of encounters that an aircraft might have with the vortex wake of a preceding aircraft on approach to an airport. Of those shown, an axial encounter is the most likely to occur at an airport because aircraft on approach are constrained to a single flight corridor for each runway. As illustrated in Fig. 1, the hazard depends on the encounter direction. Since aircraft follow each other for landing and takeoff, the most likely penetration direction is one aligned with the path of preceding aircraft which is approximately parallel to the vortex centers as shown in Fig. 1. If the path is near a center of a vortex, the following aircraft can experience overpowering rolling moments. An uncontrollable roll excursion near the ground on landing could cause flight safety to be compromised. When the flight path is well outboard or inboard of vortex centers, the wake consists primarily of upwash or downwash. Under those circumstances, the encountering aircraft can usually cope with the vortex-induced flow field so that a landing can be executed safely. In the past, wake-vortex research programs have concentrated on the axial or along-vortex encounter because it is the one that has a significant impact on airport capacity and safety.

Across-vortex encounters while on approach to an airport as shown in Fig. 1, are unlikely because air traffic controllers strive to keep aircraft in flight corridors aligned with runways. Encounters across a vortex wake can occur if aircraft make a go-around or are simply flying across an airport. When an across-vortex encounter does occur, the aircraft experiences severe vertical loads of short duration brought about by the up- and downwash in lift-generated wakes (Fig. 2). If the encounter is not perpendicular to the vortex axes, but a slanting encounter, the vortex-induced loads include both vertical- and rolling-type disturbances that can be severe.

When aircraft are in their cruise configuration and at cruise altitude, Fig. 3, the likelihood of the encounters described in the foregoing paragraphs for airports is also present at cruise altitudes, because aircraft often use about the same routes to travel between destinations. Once again, the up- and down-wash in a lift-generated wake is similar to that presented in Fig. 2. However, the rolling-moment hazard is usually mitigated when aircraft are in cruise because the in-trail spacing between aircraft is usually large enough that the mutually-induced, or Crow[7,8], instability for a vortex pair destroys the coherent structure of the wake. Once the rotational flow field of the vortex pair becomes incoherent, the vortex wake loses its ability to produce large rolling moments and becomes essentially non-hazardous for along-wake penetrations. However, caution should be exercised because, when certain atmospheric conditions exist, the mutually-induced instability may not occur[8,9]. The severe rolling-moment hazard posed by the wake then persists for longer than a few minutes behind the wake-generating aircraft before decomposing due to other decay processes.

If, as illustrated in Fig. 3, an aircraft in cruise makes an across-track penetration of a vortex wake, the rotory motion of the air in the vortices (or the overall up- and down-wash momentum of the air that is associated with the lift on the generating aircraft) can cause severe vertical, short-duration or impulsive-type loads, just as in the airport vicinity. The vertical loads come about because, as the aircraft crosses through a lift-generated wake, the downwash distribution (Fig. 2) changes the instantaneous angle of attack of the aircraft, and consequently the lift, by substantial percentages. The changes in angle-of-attack caused by the downwash in the wake are aggravated in cruise because the wing is at smaller angles of attack than on approach. Also of concern is the fact that wake encouanters of the crossing type will become more frequent at cruise altitudes when the so-called free-flight concept is put into practice and airlines are permitted to choose any path they wish between airports. Although small in-trail spacings between aircraft in cruise will usually not be chosen, the likelihood of flight paths crossing or coming near the lift-generated wakes of other aircraft could increase substantially with free flight. The hazard posed by severe vertical loads of short duration are then likely to become much more frequent because the downwash in the wake spreads so slowly that it persists for tens of minutes throughout a long narrow region behind the wake-generating aircraft. A long downwash region comes about because the spreading of lift-generated wakes appears to be controlled by a laminar type of diffusion rather than by turbulence in the ambient air, or by turbulence brought about by the wake itself. The downwash distribution and its associated hazard are therefore coherent for long periods of time which confines the downwash to a long narrow region behind the wake-generating aircraft. Any motion of the wake region that does occur is brought about by the small self-induced downward velocity of the vortex pair, and by the motion of the ambient fluid. Although the length of a hazardous downwash region has always existed, its presence will become more apparent as wake crossings become more frequent under the free-flight policy.

In principal, both the axial- and across-vortex penetrations have the same influence on the encountering aircraft whether the incident occurs in the airport vicinity or at cruise altitudes. The influence and the magnitude of the rolling or vertical stress placed on the encountering aircraft does however differ in a number of ways. First, the velocities of the wake-generating and following aircraft on approach and during cruise are from 150 to 200 kts., which requires a high-lift configuration. That is, whenever aircraft are in approach or departure situations they are in a high-drag configuration with slats, flaps and landing gear deployed. Conversely, while aircraft cruise between destinations, they are in a low-drag configuration with flaps, slats and landing gear stowed and flying at velocities in excess of 500 kts. Also, while across-vortex penetrations are fairly easy to prevent in the vicinity of an airport where the flight paths of all aircraft are controlled, thereby making the locations of vortex wakes fairly well known, such is not the case at cruise altitudes. In addition, flight corridors line up with runways and are quite small in number near an airport for approach, whereas, in cruise the flight corridors are large in number and they go in a variety of directions. For these reasons, in approach corridors axial encounters with vortices will be much more numerous, and at cruise altitudes across-wake encounters will be the ones that can cause more problems. Another difference between the approach and cruise problem is that while on approach very little altitude is available for recovery from a strong vortex encounter, whereas while at cruise altitudes a great deal of altitude is available. This difference has contributed to the perception that vortex wakes do not pose a hazard at cruise. Since noticeable vortex-induced rolling excursions are extremely rare during cruise and extreme vertical-load encounters can be attributed to a number of 'clear air' irregularities in the atmosphere, a wake-vortex hazard is often believed not to exist at cruise altitudes.

Finally, examination of a bibliography by Hallock[10] indicates that a large difference in research effort has gone into the study of the potential hazard posed by vortex wakes in the airport environvment as compared with the work on lift-generated wakes at cruise altitudes[11–22]. The reason for the large difference in effort put forth is that a solution to the wake-vortex problem at airports would have a direct impact on capacity, safety, economy of flight. The impact of a solution at cruise altitudes is perceived to be small. That is, since most hub airports are now at or near maximum capacity during certain parts of the day, a solution to the vortex wake problem at airports would have a direct economic and safety benefit. A comparable motivation to understand the dynamics and persistence of lift-generated wakes at cruise altitudes has not been identified because the large space available for flight is not congested enough for a significant wake hazard to be perceived. In fact, pilots often have the perception that a wake-vortex hazard does not exist anywhere except in the vicinity of airports where aircraft are constrained within narrow flight corridors during landing and takeoff.

The purpose of the study reported here is to determine the extent of the hazard posed by aircraft as they cruise between destinations. Since much of the information about the dynamics of vortex wakes shed by aircraft is found by observing the condensation wakes at cruise altitudes, a description is first given of the conditions required for the wakes to become visible. Since the problem associated with along-vortex penetrations has been studied extensively and is well documented, only the background of across-vortex penetrations is presented. Included is an overview of the research that has been conducted on lift-generated vortex wakes associated with aircraft as they cruise between destinations. In order to evaluate the hazard posed by vortex wakes at cruise altitudes, a review is given of the menhods used to calculate the loads along with new methods for the across-wake penetration cases. With the background supplied by this information, a description is then given of the various stages that vortex wakes go through as they age behind aircraft at cruise altitudes, along with an estimate of the magnitude and persistence of the hazard posed at each stage of aging. Any shortcomings in the knowledge required to evaluate the hazard will be identified. It is the intent of the paper to present enough information so that realistic estimates can be made of the impact of the hazard on airline routes. Since it is found that across-wake encounters will probably become more prevalent, and will pose safety concerns for aircraft and passengers, an outline of wake-avoidance procedures that can be used to prevent encounters while aircraft cruise from one destination to another is also provided.

Visualization of Wakes by Exhaust Condensation

Since much of the information presented in this paper is based on observations made of the condensation wakes of subsonic transports at cruise altiude[23-26], it seemed appropriate to first present information on when water from jet exhaust condensation is not seen, when it is visible, and when it persists for long periods of time. Scorer and Davenport[23] made observations on the dynamics of vortex wakes and presented an overview of when the exhaust from aircraft engines would condense at cruise altitudes. A recent article on the formation of condensation wakes from water vapor in jet engine exhaust by Sassen[24,25] provides a more current and complete set of information and data on when condensation wakes appear and when they persist. The reader is referred to Sassen's articles for more information on the process and on estimates of how various parameters associated with weather and climate are affected by cirrus clouds and condensation wakes. It is pointed out that jet condensation wakes are often visible when natural cirrus clouds are present. The temperature and humity combination at which condensation wakes form are shown in Fig. 3, which is reproduced from Sassen's[24] article. The data also indicates when wakes are visible for long periods of time and when not. As explained by Sassen, the condensation trails that persist are those that occur in regions where the temperature is colder than about $-40^o C$ and the relative humidity is over about 30%. Humidity is required to prevent rapid evaporation, and low temperatures are required so that the water droplets from the cooling exhaust freeze as they are formed. If the droplets remain as water, rather than as ice crystals, they evaporate quickly and the wake disappears.

The data shown in Fig. 4 indicates why vortex wakes are clearly visible some times of the year and not at others. For example, in the San Francisco Bay Area vortex wakes are seldom visible during the warm months (i.e., May through September) and often visible during the colder and wetter months of the year (i.e., January and February). Since much of the data to be presented was obtained from photographs of vortex wakes over the Bay Area, it is assumed that they are typical of wake dynamics throughout the year. An illustration of the persistent visibility of vortex wakes and the large numbers of aircraft wakes that can sometimes appear overhead at a given time is presented in Fig. 4; from Mims and Travis[26]. Since condensation wakes are so prevalent, a number of research efforts have been directed at determining what effect the extra cloud cover that they represent has on weather and climate[24-26]. It is from studies such as these that the information in Figs. 3 and 4 was obtained. In Fig. 4, the wakes shed recently are noted to have very narrow condensation trails whereas older trails get progressively broader as they age. Observations of condensation trails on days when they persist for long periods of time indicate that wakes spread by as much as or more than 100 times the span of the generating aircraft one or more hours after the wake was generated. More often, the condensation particles (water droplets or ice crystals) evaporate enough that the wakes disappear after 5 to 10 minutes.

Observation of the condensation trails of aircraft does provide flow visualization of many aspects of the aerodynamics of wakes at little cost. Another advantage is that the low pressure core regions of vortices entrain low density gases from engine exhaust and thereby highlight the time-dependent history of the centers of lift-generated vortices. It should be kept in mind, however, that a large number of wakes during daylight hours and those at night are not visible by condensation and therefore not observable. Since atmospheric conditions for production of condensation differ only a little from those that do not, and only a small percentage of the total energy in the wake is involved in the condensation process, it is assumed that the behavior of visible and invisible lift-generated wakes shed by subsonic transport aircraft are the same. Nevertheless, it will be prudent to check this assumption if an avoidance scheme is to be implemented that relys on specific characteristics of vortex wakes that might be changed by the atmospheric conditions associated with condensation. For example, presence of the jet stream may affect the structure, spreading rate, and especially the transport of vortex wakes. Therefore, the lack of wake visibility through condensation brings uncertainty as to the time-dependent dynamics and location of vortex wakes which are used to determine the hazard posed. Although similar concerns were expressed during the early days of wake-vortex research, a systematic difference between the decay of vortices in air or in water was not detected so that all exhibited somewhat the same type of plateau and $t^{-1/2}$ decay behavior observed by Ciffone and Orloff[27]. Furthermore, the data correlation carried out by Iversen[28] did not indicate any systematic differences between data sources or facilities. It is well known however, that the turbulence in the wake region within the first tens of spans behind the wake-generating aircraft plays a major role in the initiation of mutually-induced instabilities which are effective mechanisms for the rapid destruction of the coherent nature of the flow field produced by a vortex pair[7,8].

Background on Across-Wake Penetrations

McGowan[11] was one of the first to recognize the potential hazard posed by the vortex wakes of aircraft and to then proceed to estimate the various loads that vortex wakes impose on aircraft that encounter them. The paper also provides the results of an extensive set of computations that indicate the seriousness of the problem for many encounter situations. McGowan's paper concentrates on the dynamics experienced by aircraft as they cross at right angles through the center of a lift-generated wake. Analysis of the wakes of three sizes of wake-generating aircraft points out that, as expected, the wakes of larger generating aircraft cause larger imposed vertical loads on penetrating aircraft. Even with the smallest of the generator aircraft the imposed vertical loads can exceed one g relative to normal gravity in upward and downward directions. In the wakes of the larger aircraft, the imposed loads may exceed the structural limits of the penetrating aircraft. McGowan also computed paths of the encountering aircraft during and after wake penetration by assuming both that the controls were fixed and that the controls were deflected in order to alleviated the loads. It was recommended that the encounter be executed with controls fixed because the time-dependent loads oscillate so rapidly that pilot input could easily be of such a phase that they aggravate rather than alleviate the loads. McGowan's computations were based on the structure of the wake in the near field behind the wake-generating aircraft and an estimate of the rate of diffusion or spreading of the wake with time or distance was not presented. Since the downwash wake does diffuse or spread with time, the imposed vertical loads decrease with time or distance behind the generator aircraft so that McGowan's calculation represent maximum loads. The results in McGowan's paper[11] suggest that some recent encounters[29,30] with "clear air" turbulence might have been caused by an across-trail penetration of a lift-generated wake.

Some work by the Royal Aircraft Establishment in England reported by Rose and Dee[12] and by Bisgood, Maltby and Dee[13] confirm McGowan's computations by providing flight measurements on the across-wake penetrations by a Lincoln aircraft (66,000 lbs.) in the wakes of a Comet 3 and a Vulcan 1 aircraft (100,000 lbs.). The measured data indicates the kinds of trajectories that penetrating aircraft can experience. Since the weight ratios between the wake-generating and penetrating aircraft are not as large as those considered by McGowan, the vertical loads are around 0.3 g both upward and downward from steady-state flight, which is not as extreme as predicted by McGowan. Since the measurements were all made within several minutes behind the wake-generating aircraft, data was not obtained on the persistence of the hazard posed by vertical loads.

The paper by Conduit and Tracy[14] decribes results from an extensive test program conducted by The Boeing Company on the potential hazard of aircraft in their cruise and landing configurations. Aircraft types include an F-86, B-737, B-707-320C, B-747, CV-990, and C-5. The paper is of value not only for the encounter data and for the data on the changes in vortex wakes with distance behind wake-generator, but also for the pilot comments which are included.

Methods for calculating the loads induced on aircraft making across-wake penetrations are described by Houbolt[15] and by Jones and Rao[16]. Houbolt's theoretical estimates indicate that vertical loads above steady flight in excess of 2 g's are likely if the encountering aircraft is much smaller than the generator and about 0.4 g when they are both about the same size. The examples considered by Jones and Rao assume that the penetrating aircraft are about two vortex spacings above the plane of the vortex centers. As a consequence, the encounters are not as severe. Jones and Rao's method is such that encounters from any approach angle can be analyzed. Their method is analytic in nature and does not rely on high-speed computers as much as more recent methods for calculating loads. In both the method of Houbolt and of Jones and Rao the loading on the encountering wing was determined by use of a Fourier series representation of the span loading similar to that described in Chapters X and XI of Glauert[31]. The method of Jones and Rao was applied by Ramirez, Rao and Cronk[17] to the encounter of a De Havilland Beaver with a vortex wake shed by a B-747 at an encounter angle of 5°. They present the magnitude of the vertical and rolling moment loads along with the longitudinal stability of the penetrating aircraft.

Nelson[18,19] presents an analysis that permits the computation of the response dynamics of aircraft as they encounter vortex wakes at a wide variety of encounter angles from axial to perpendicular encounters. He states that trial computations indicate that lifting-line/strip theory provides about the same results as more complex theories. The simpler load predicting method made it possible to carry out simulations of encounters on a six degree-of-freedom model for three aircraft sizes; i.e., business aircraft (15,000 lbs.), DC-9 (70,000 lbs) and a Convair 990 (153,000 lbs). The computations present data for near axial encounters and downstream distances up to 10 miles and for perpendicular penetrations. In one example, the computations indicate vertical loads for the business jet in the wake of a DC-9 that alternately exceed one g in less than a second. As stated previously, he also concluded that stick fixed loads are usually less than those where load alleviation is attempted.

The three remaining references, McWilliams[20], Britton[21] and Pinsker[22], present information on wake encounters while aircraft are at cruise between destinations. Those results serve to indicate whether theoretical predictions are realistic or not. This information will be described in more detail as it is used in sections to follow wherein wake structure at various times are described along with an estimate of the hazard that might accompany that stage of vortex decay.

Computation of Wake-Vortex Induced Loads

Along-Axis Penetrations

As mentioned in the introduction, a great deal of effort has been expended on the study of vortex wakes at and in the vicinity of airports. Several summaries of that work as it progressed with time are presented in Refs. 1-6. The research efforts summarized there include predictions and measurements of the rolling moments for a wide variety of aircraft combinations along with some results on methods for decreasing the magnitude of the rolling-moment hazard posed by lift-generated wakes of subsonic transport aircraft[6,32-35]. In addition, approximate closed-form relationships[36] have been derived for the lift and rolling-moment coefficients induced on a following wing when a near or centered axial penetration occurs. Measurements in the large wind tunnels at NASA Ames Research Center[32-34] and in flight[35] have confirmed the accuracy of a vortex-lattice code for computing the rolling-moment loads on following wings. The results indicate that the method is very accurate and adequate when the following wing is less that about 25% of the span of the wake-generating wing, but as the span increase errors increase gradually in certain parts of the flow field to about 30% when the following and generating wing are the same size[34]. The explanation for the increase in error is that the larger wings distort the vortical flow field enough to modify the downwash distribution from that assumed in the theoretical method for calculating the loads. Based on wind tunnel and flight test results it is concluded that the loads to be expected when a following aircraft makes an axial encounter with a vortex can therefore be estimated fairly accurately.

Across-Axis Penetrations

Methods Currently Available

Comparable theoretical analyses and measurements have not been carried out for the across-wake penetration situation for a number of reasons. First, the loads are of short duration which requires that the analysis method account for the time required to establish the flow field around the wing and to move away from the spanwise vortex that is shed when the lift changes. Secondly, laboratory simulation of across-vortex encounters and the measurement of the loads induced on the penetrating wing are very difficult. (Conversely, the simulation of axial encounters in a wind tunnel are natural to the facility.) Lastly, a strong interest was not expressed in the consequences of across-vortex encounters because they could be prevented at airports where capacity and safety was of primary concern.

Even though a comparable volume of information is not available on the loads induced on an aircraft as it makes a crossing encounter with a lift-generated wake, previous observations and analyses carried out on crossing encounters[11-20] does serve as a foundation for the present study. The various analyses assumed a downwash profile typical of those measured a short distance behind the wake-generating aircraft (e.g., Fig.2), and not like a disorganized wake that consists primarily of downwash without highly coherent vortices. Therefore, a highly reliable method for calculating the downwash-induced loads on an aircraft as it crosses a wake must first include a realistic estimate of the lift-generated wake at the time of crossing. The method should also account for the reduction in load intensity caused by the short time of encounter, and for the effect of compressibility on the flow field at the velocities used by aircraft in cruise.

Methods Based on Momentum Considerations

Work is underway on the development of a method to estimate the maximum vertical loads that are likely when an aircraft makes a crossing encounter with the downwash from a lift-generated wake.

Stages of Wake Decay Behind Aircraft During Cruise

The photographs of condensation wakes behind aircraft at cruise altitudes have been taken and are now being sorted, selected and processed for presentation in this section. Each stage of decay to be illustrated in the photographs to be presented will be interpreted in the final version of the paper for wake dynamics and for any rolling-moment or vertical-loads hazard that is estimated for that stage.

Rollup of Vortex Sheet

Instability Initiation

Division of Wake

Execution of Instabilities

Reassembly of Wake Parts

Organization Into In-Trail Segments

Spreading and Decay of In-Trail Segmemts

Rate of Wake Spreading

A theoretical estimate will be made of the rate at which vortex wakes spread as they age. On a graphical representation of those expressions, data obtained from condensation trail will be plotted.

Modification of Aircraft to Alleviate Loads

The prospect of modifying the wake-generating aircraft so that it does not shed a hazardous wake has been studied since around 1970. Some of these theoretical studies and experimental results indicate that the dissipation or disorganization of vortex wakes can be accomplished by special wing designs so that the rolling moment hazard can be significantly reduced for approach configurations of transport aircraft. A comparable demonstration of significant alleviation of the hazard posed by the downwash of aircraft wakes at cruise or in the airport vicinity has not been demonstrated nor are methods for more rapid spreading of the wake been suggested. The spreading of the downwash is a much more difficult problem to solve than is the one associated with the rolling-moment hazard, primarily because the lift on the wing has as a consequence the downward momentum of air over an area on the order of the span of the wing. The most obvious way to reduce the downwash velocities is to go to larger wing spans. However, even a doubling of the wing span would only reduce the vertical loads by a factor of two, when it is estimated that at least a factor of ten is needed. Even a small increase in wing span has significant negative implications on the performance and efficiency of subsonic transports. Also, if implemented, modification of the existing fleet would be very expensive, or would require that alleviation could be applied to only new aircraft. More importantly, such a change would probably decrease the flight efficiency of aircraft significantly. It may be possible to invent some sort of tailored span loading that causes the downwash distribution to spread much more rapidly that conventional designs. All indications from past experience indicate, however, that it is not possible to do so; especially when the large amount of spreading required to make the wake downwash non-hazardous is noted. If an acceptable solution were to be found, it would probably require extensive modification of the generating aircraft or of purchasing new aircraft. Either way, the cost will probably be prohibitive because modification and new aircraft expensive.

A Wake-Avoidance Procedure

An outline will be presented of procedures based on the Global Positioning System that will make it possible for aircraft to avoid lift-generated wakes while in cruise.

Concluding Remarks

The overview study to be reported in the proposed paper will discuss and justify the following conclusions. The results to date indicate that lift-generated wakes at cruise altitudes include downward momentum (that is associated with the lift on the wing) which is even more persistent than the intense rotary velocities associated with the rolling-moment hazard in the airport vicinity. Previous studies of the rolling-moment hazard associated with lift-generated wakes show that the hazard usually appears to decay to a harmless level within several minutes behind the wake-generating aircraft. The downward momentum brought about by the lift on the wake-generating wing, however, is estimated to persist at a hazardous level for tens of minutes. As a consequence, the hazard posed by aircraft wakes exists throughout a long slender tube of air behind an aircraft at cruise altitude. In that tube, only a small rolling-moment hazard is posed to aircraft that make an in-trail encounter, but when across-wake encounters occur, the penetrating aircraft may be exposed to severe vertical loads of short duration that could compromise passenger and flight safety. The hazard posed by the downwash appears to fade away slowly as the wake spreads laterally so that an end is difficult to define. Although present encounters with downwash wakes are rare, more frequent incidents are expected in the future as air traffic increases, and when the free-flight concept is put into practice, if steps are not taken to avoid wake encounters.

It is therefore concluded and recommended that vortex wakes should always be avoided when possible and that no aircraft should ever intentionally enter a vortex wake unless it is conducting a well-designed research program. Even then, it should be remembered that entering a vortex wake can be a very hazardous undertaking.

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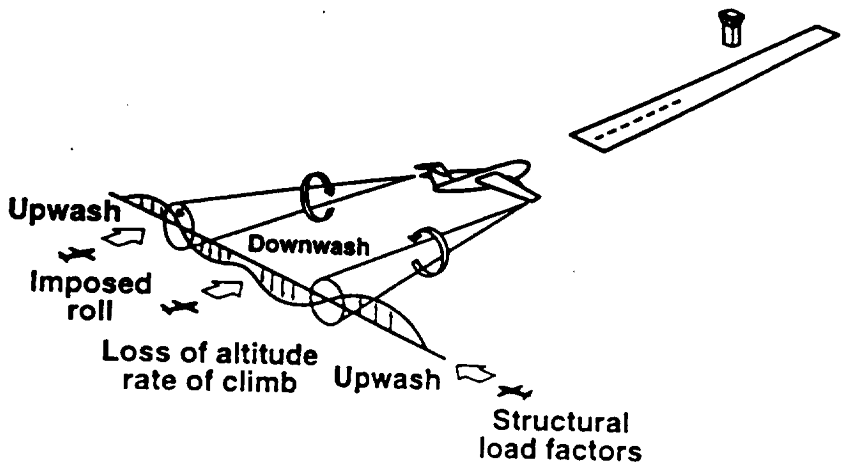

Fig. 1 Possible encounters by an aircraft while on approach to an airport with a lift-generated wake shed by a preceding aircraft[6].

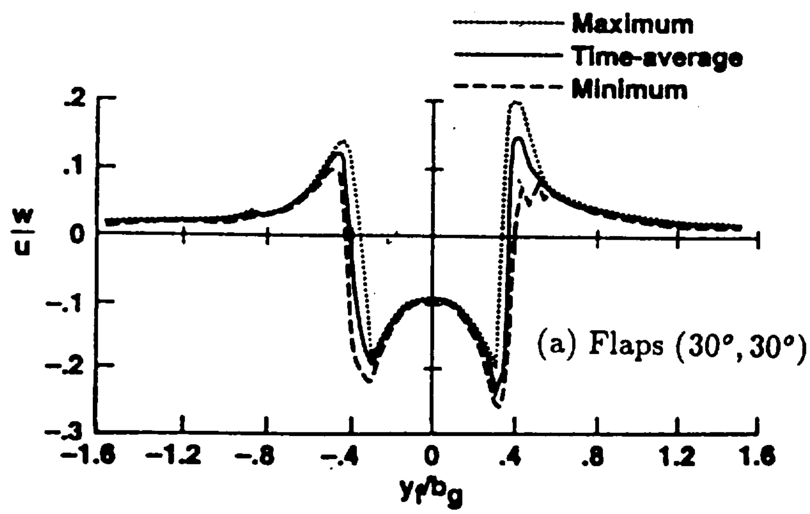

Fig. 2 Up- and downwash distribution typical of lift-generated wakes behind large aircraft in their landing configuration as measured in a wind tunnel at one-half mile scale distance behind the wake-generating aircraft[6].

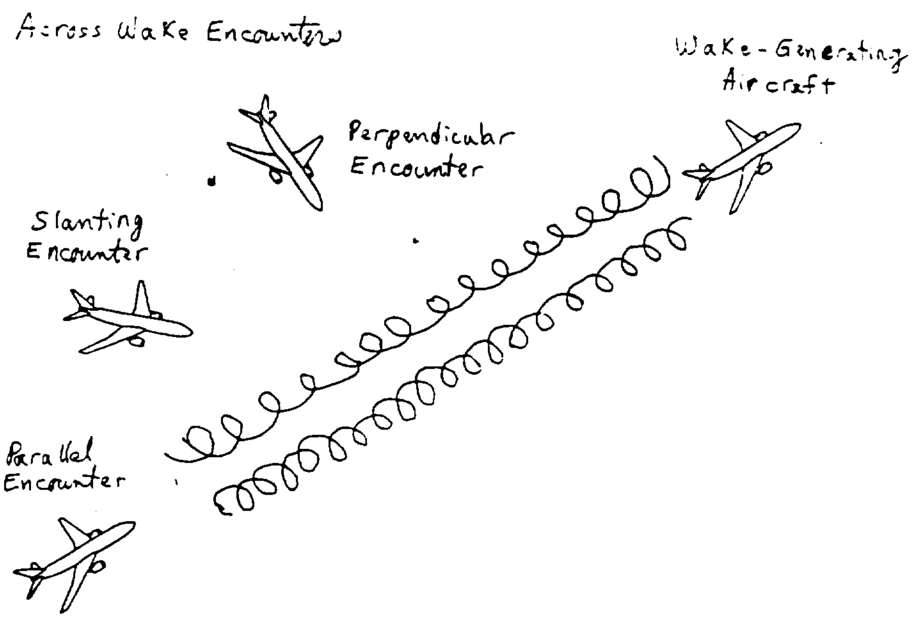

Fig. 3 Possible encounters by an aircraft while at cruise altitude with a lift-generated wake shed by a preceding aircraft.

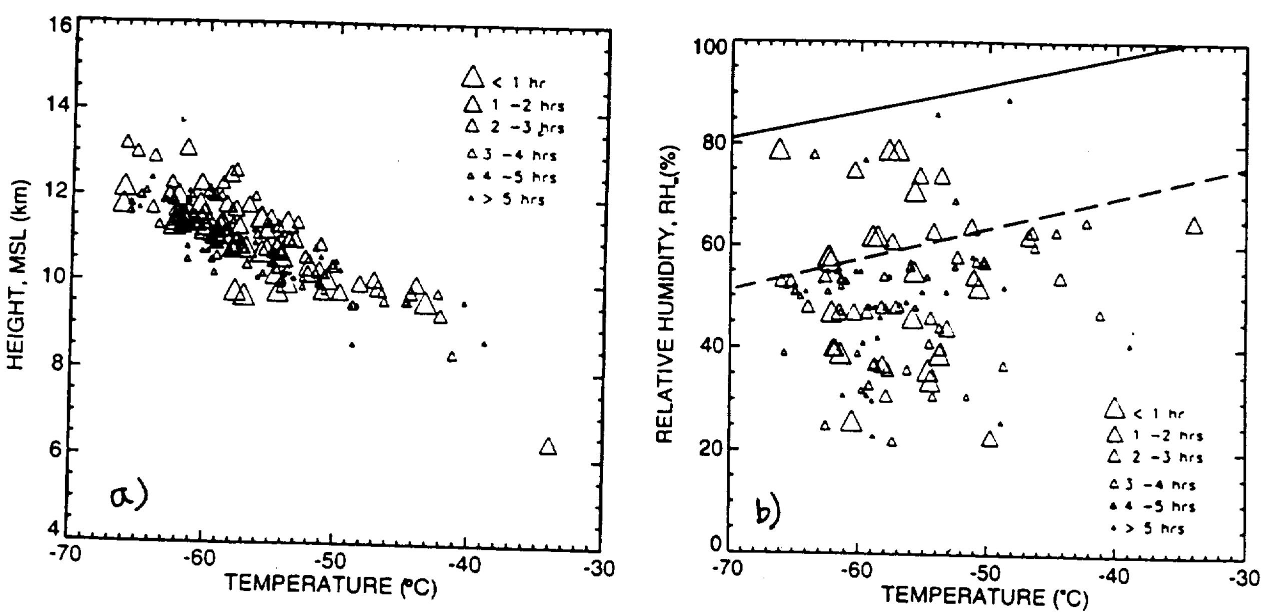

Fig. 4 Scatterplots showing the relationship between (a) FARS ruby lidar-derived contrail height and local sounding temperature (178 contrails) and (b) contrail-level temperature and relative humidity with respect to water (106 contrails). The dashed line in (b) indicates the ice saturation level, and the solid line shows the Sassen and Dodd[2] threshold relationship for natural cirrus cloud formation. The size of the data points reflects the time between the nearest 12-hour Salt Lake City/National Weather Service launch, such that the larger the symbol, the more reliable the data (see inserted key). From Sassen[24].

Fig. 5 Dense condensation trails caused by air traffic over Lausanne, Switzerland in Nov. 1996. Photo by F. M. Mims III; from Mims and Travis[26].